

Discovery of transient high-energy γ -ray emission from the BL Lacertae object 5C 3.178

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ABSTRACT

We report the serendipitous discovery of transient, point-like high energy γ -ray emission coincident with the position of the suspected BL Lac object 5C 3.178. The source was detected using the *Fermi* Large Area Telescope (LAT) at a significance level of $\sim 8\sigma$ during a 200 day period which began on November 17th 2011 (MJD 55882). The observed γ -ray emission is characterised by a moderate 0.2-300 GeV flux $F_{0.2-300\text{ GeV}} = (8.22 \pm 2.04) \times 10^{-9} \text{ ph cm}^{-2}\text{s}^{-1}$ and a hard power law spectrum with spectral index $\Gamma = 1.76 \pm 0.09$. These properties appear consistent with the known sub-population of TeV γ -ray-emitting BL Lac objects, implying that the source may be detectable using atmospheric Cherenkov telescope arrays. Moreover, the temporal variability of the source suggests that real-time searches of the *Fermi*-LAT all-sky dataset for weak emission on ~ 200 day timescales may represent a rewarding strategy.

Key words. Astroparticle physics - Gamma rays: galaxies - BL Lacertae objects: individual: 5C 3.178

1. Introduction

Active Galactic Nuclei (AGNs) are compact, energetic astrophysical phenomena associated with the cores of many galaxies, which are paradigmatically assumed to be powered by disk accretion onto a supermassive ($M \gtrsim 10^8 M_\odot$) black hole. A sizeable fraction of AGNs are also launch sites for relativistic jets of plasma, which emit broad-band radiation with non-thermal energy spectra that extend from radio to γ -ray frequencies (e.g. Urry & Padovani 1995).

BL Lacertae objects (hereafter BL Lacs) are a subset of AGNs that have jet axes that are oriented close to the observer's line of sight. The observed spectral energy distributions (SEDs) of BL Lacs are dominated by relativistically beamed emission from charged particles entrained in the jets and exhibit a characteristic two-component structure. The individual components are visible as low and high energy peaks in a νF_ν representation of the SED and are typically identified with distinct radiative processes occurring within the jets. The low energy component is usually attributed to synchrotron emission while inverse-Compton up-scattering of this synchrotron emission or other ambient soft radiation fields is assumed to dominate at higher energies.

BL Lacs are an established class of variable high energy (HE; $10^{-3} \lesssim E_\gamma/\text{GeV} \lesssim 50$) and very high energy (VHE; $10^{-3} \lesssim E_\gamma/\text{TeV} \lesssim 10^2$) γ -ray sources. Indeed, the second *Fermi*-LAT (2FGL) source catalogue includes 435 confirmed BL Lac objects, of which 36 have also been detected at TeV energies (Nolan et al. 2012). In a recent review, Şentürk et al. (2013) examined the *Fermi*-LAT light curves of 12 established VHE γ -ray-emitting BL Lacs, which reveal significant flux variability on timescales ranging from days to months. Furthermore, a population study of 395 BL Lac objects listed in the second *Fermi*-LAT AGN catalogue

(2LAC) also revealed clear evidence for HE variability, although it is apparently less prevalent in sources with hard γ -ray spectra (Ackermann et al. 2011).

5C 3.178 is a point-like radio source located to the southeast of M31 at $(\alpha_{J2000}, \delta_{J2000}) = (00^{\text{h}}47^{\text{m}}55^{\text{s}}.220, +39^\circ48'57''.60)$ (Mao 2011). The source was initially discovered using the Cambridge one-mile radio telescope (Pooley 1969) and has been provisionally identified as a BL Lac object based on the absence of detectable emission features in its optical spectrum (Burbidge & Hewitt 1987; Djorgovski et al. 1995). Multi-wavelength counterparts have been identified at near infra-red (Skrutskie et al. 2006; Mao 2011), optical (Djorgovski et al. 1995), ultraviolet (Fittingoff et al. 2009) and X-ray (Voges et al. 1999; Saxton et al. 2008) frequencies. A source redshift of $z = 0.2517 \pm 0.001$ has been established on the basis of optical absorption features imprinted by the host galaxy (Djorgovski et al. 1995).

The Large Area Telescope is the principal scientific instrument on the *Fermi* Gamma Ray Space Telescope spacecraft. It is a pair conversion telescope with a ~ 1 m effective area, which is sensitive to photons with energies between 20 MeV and 300 GeV. The field of view of the *Fermi*-LAT encompasses 2.4 steradians, and the instrument typically operates in a continuous survey mode, providing all-sky coverage every two orbits. The operation and performance of the *Fermi*-LAT are described in detail by (Atwood et al. 2009).

This article describes the discovery and analysis of a point-like γ -ray signal coincident with the position of 5C 3.178, which was serendipitously identified while searching unsuccessfully for HE emission associated with a 200 day flare of the nearby ultra-luminous x-ray source (ULX) XMMU J004243.6+412519 (Middleton et al. 2013). Sec-

tion 2 describes details of the data selection and analysis procedure which were employed to produce the results presented in section 3. Section 4 discusses the implications of this detection in the context of HE and VHE γ -ray emission from BL Lac objects.

2. Data Analysis

The *Fermi*-LAT data were analysed using version v9r27p1 of the Fermi Science Tools¹ in conjunction with the P7SOURCE_V6 (Pass 7) instrument response functions. The dataset under consideration was extracted from a circular region of interest (ROI) of radius 10 degrees centred on 5C 3.178 and comprised all SOURCE class photon-like events detected by the *Fermi*-LAT before MJD 56282 (2012-12-21) with energies between 200 MeV and 300 GeV. Good time intervals (GTIs) were generated using the recommended selection expression² and ROI-based maximum zenith angle cut³, before being applied to isolate subsections of the data for subsequent analysis.

The reduced data were analysed using an un-binned maximum likelihood approach (Mattox et al. 1996) implemented by the `gtlike` utility⁴, in which two alternative model hypotheses were compared by maximising their respective likelihoods with respect to the the observed photon distribution. As a nominal *null* hypothesis, the expected γ -ray signal within the ROI was modelled using a combination of the standard galactic (`gal_2yearp7v6_v0`) and isotropic (`iso_p7v6source`) diffuse emission models. The model also incorporated all point-like γ -ray emitters within 20° of 5C 3.178 that are listed in the 2FGL catalogue. To prevent genuine variability or statistical fluctuations of the signals from nearby γ -ray emitters from affecting the analysis, the overall flux normalisations of sources within a 10° radius of the target were treated as variable parameters. In order to ameliorate any local mis-modelling of the diffuse γ -ray emission within the ROI, the overall normalisations of the isotropic and galactic template components were also allowed to vary during the likelihood analysis. To limit the number of degrees of freedom in the final likelihood, the remaining source model parameters were fixed to the best fitting values published in the 2FGL. A second, *alternative* hypothesis included a model for putative emission from an additional point-like γ -ray source with a power-law spectral shape parameterised as

$$dN/dE = N_0(E/E_0)^{-\Gamma}. \quad (1)$$

The normalisation (N_0) and spectral index (Γ) were allowed to vary during the likelihood optimisation, while the energy scale (E_0) was fixed to 1 GeV.

Evidence for the detection of an additional HE γ -ray source was evaluated in terms of a likelihood ratio test statistic

$$TS = -2 \ln \frac{L_{\max,0}}{L_{\max,1}} \quad (2)$$

¹ <http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/overview.html>

² `(DATA_QUAL==1) && (LAT_CONFIG==1) && ABS(ROCK_ANGLE)<52`

³ This cut excludes all time intervals when the zenith angle of any part of the ROI exceeds 100°.

⁴ <http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/http://gtlike.sourceforge.net/>

where $L_{\max,0}$ and $L_{\max,1}$ are the maximum likelihood values obtained when fitting the observed data using the null and alternative hypothesis models respectively. If the null hypothesis is true, then \sqrt{TS} is approximately equivalent to the source detection significance in the framework of standard normal theory.

3. Results

As explained in §1, the initial source detection corresponded to *Fermi* data that were obtained during the 200 day flaring cycle of the ULX XMMU J004243.6+412519. A subsequent analysis of the complete *Fermi*-LAT dataset revealed strong evidence ($TS = 54.1 \approx 7.4\sigma$) for a spectrally hard ($\Gamma \approx 1.7$) point-like HE γ -ray source close to the position of 5C 3.178, with a time-averaged 0.2-300 GeV flux of $(1.78 \pm 0.79) \times 10^{-9}$ ph cm⁻²s⁻¹. Given its apparent brightness, the absence of this source from both the first and second *Fermi*-LAT source catalogues (Abdo et al. 2010; Nolan et al. 2012) suggests a transient origin for the observed γ -ray emission. In the absence of any *a-priori* expectation for likely variability timescales, the overall dataset was subdivided into 200 day intervals (labelled A-H) to match the duration of the initial detection dataset. Each interval was individually re-analysed to obtain the results listed in Table 1 and illustrated in Figure 1.

Assuming that the test statistic is approximately χ^2_1 distributed (Mattox et al. 1996), then the probability of obtaining a value of TS which exceeds some threshold TS_0 in a *single trial* is

$$P_1(TS \geq TS_0) = \int_{TS_0}^{\infty} \chi^2_1(x) dx \quad (3)$$

Under the reasonable assumption that the measured γ -ray signals corresponding to non-overlapping time slices are statistically independent, then the probability of obtaining a $TS > TS_0$ *at least once* after testing all 8 sub-intervals is

$$P_8 = \sum_{i=1}^8 \binom{8}{i} P_1^i (1 - P_1)^{8-i} \quad (4)$$

Defining Φ^{-1} to be the complement of the quantile of the χ^2_1 distribution, P_8 can be used to derive a trials-corrected test statistic

$$TS' = \Phi^{-1}(P_8). \quad (5)$$

A trials-corrected test statistic value of $TS' = 58.9$ ($\approx 7.7\sigma$) provides clear evidence for transient γ -ray emission during interval G, which begins on MJD 55882 (2011-09-17). Further subdivision of interval G into 10 week, 2 week and 1 week time slices does not reveal significant flux variability on shorter timescales. The source was not conclusively detected during any other interval, although there is marginal evidence for emission ($TS' \approx 8.5$) during interval H. For intervals yielding $TS < 9$, Table 1 lists 95% confidence level upper limits on the 0.2-300 GeV flux, which are also plotted in Figure 1. The time-resolved analysis also reveals that the source would not have been detectable during the first 24 months of the *Fermi* mission, which explains its absence from the *Fermi*-LAT source catalogues.

Given the limited duration of the detectable γ -ray emission, subsequent analyses only considered the restricted

Interval	T_{start} (MET)	T_{end} (MET)	T_{start} (UTC)	TS	TS'	Flux (0.2-300 GeV) (10^{-9} ph cm $^{-2}$ s $^{-1}$)	Γ
A	239557417	256837417	2008-08-04 15:43:36	0.0	0.0	< 2.39	...
B	256837417	274117417	2009-02-20 15:43:35	3.0	0.4	< 5.37	...
C	274117417	291397417	2009-09-08 15:43:35	3.3	0.6	< 5.80	...
D	291397417	308677417	2010-03-27 15:43:35	4.1	1.0	< 1.36	...
E	308677417	325957417	2010-10-13 15:43:35	6.8	3.2	< 7.81	...
F	325957417	343237417	2011-05-01 15:43:35	7.1	3.5	< 4.46	...
G	343237417	360517417	2011-11-17 15:43:35	63.0	58.9	8.22 ± 2.04	1.76 ± 0.09
H	360517417	377797417	2012-06-04 15:43:35	12.3	8.5	3.05 ± 1.32	1.69 ± 0.12
All	239557417	377797417	2008-08-04 15:43:36	54.1	...	1.78 ± 0.79	1.70 ± 0.15

Table 1. Analysis results corresponding to eight 200 day subintervals (A-H) as well as the complete *Fermi*-LAT dataset. Test statistic values are quoted before (TS) and after (TS') correcting for the number of independent trials. For intervals during which the source was detected such that $TS > 9$, the HE γ -ray flux and best fitting power-law spectral index (Γ) are also listed. For other intervals, upper limits to the HE γ -ray flux (at the 95% confidence level) are presented.

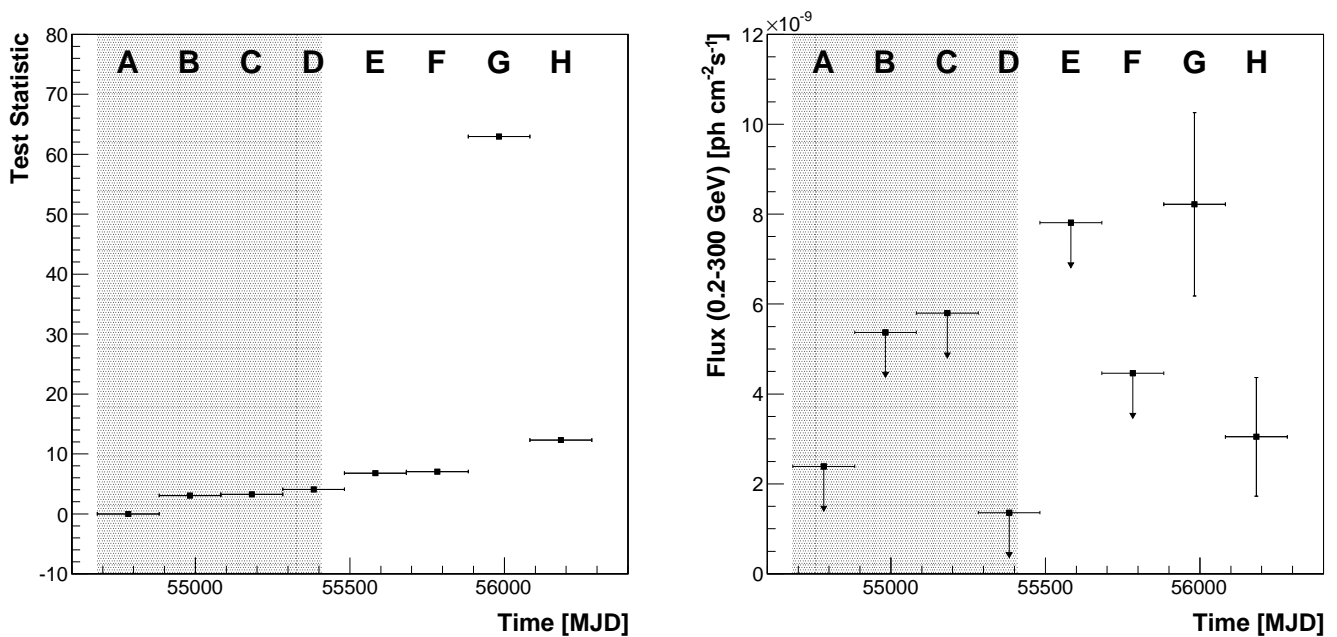


Fig. 1. *Left panel:* Values of TS corresponding to intervals A-H. *Right panel:* 95% confidence upper limits on the 0.2-300 GeV γ -ray flux are presented for intervals during which the source was not detected. The shaded areas in both plots indicate the temporal extent of the *Fermi*-LAT dataset used to compile the 2FGL catalogue (Nolan et al. 2012).

dataset of events detected during interval G, in order to maximise the signal-to-noise ratio. The `gtfindsrc` utility⁵ was applied to derive the most likely coordinates of the observed γ -ray emission, yielding $(\alpha_{\text{LAT}, J2000}, \delta_{\text{LAT}, J2000}) = (00^{\text{h}}48^{\text{m}}20^{\text{s}}.89, +39^{\circ}52'26''.1)$ with a 95% confidence error circle radius of 0.06° . Using these coordinates, the automatic source association method described by (Abdo et al. 2010) and implemented by the ScienceTools executable `gtsrcid`, was applied to search for plausible multi-wavelength counterparts to the observed HE γ -ray emitter. After considering all sources listed within the catalogues specified in Table 9 of Nolan et al. (2012), the procedure identified 5C 3.178 as the only viable candidate, deriving a posterior probability of 91% that the association is correct.

The *Fermi*-LAT data corresponding to subinterval G were used in conjunction with the `gttsmap` tool⁶ to generate the TS sky map presented in the left panel of Figure 2. To generate this map, the null hypothesis model described in §2 was used, with all parameters except for the diffuse component normalisations fixed to the best fitting values that were obtained for this subinterval during the likelihood analysis. The transient γ -ray source is clearly visible as a point-like enhancement of the computed TS values, coincident with the nominal position of 5C 3.178 (Mao 2011).

The observed 0.2-300 GeV spectral energy distribution and best-fitting power law model corresponding to interval G are presented in the right-hand panel of Figure 2. The data correspond well with the assumed model and indicate

⁵ <http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/help/gtfindsrc.html>

⁶ <http://fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/help/gttsmap.html>

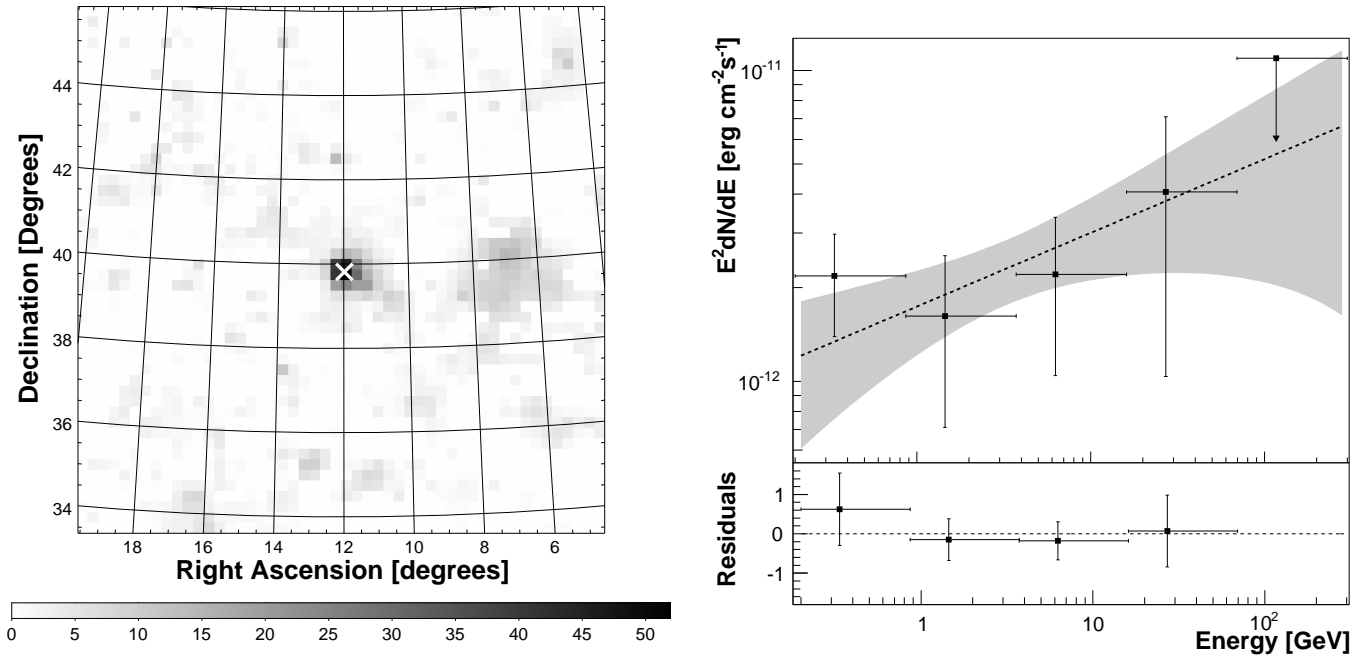


Fig. 2. *Left panel:* Unbinned likelihood test statistic map corresponding to subinterval G of the *Fermi*-LAT dataset. The white cross marks the nominal radio position of 5C 3.178. *Right panel:* HE γ -ray spectral energy distribution between 0.2 and 300 GeV corresponding to subinterval G of the *Fermi*-LAT dataset. The dotted line indicates the best-fitting power-law model, and the grey region indicates the 1σ fit uncertainties. Residuals of the observed data points with respect to the best fitting power law spectral model are also presented.

that the transient γ -ray emission is spectrally hard, with a power law index $\Gamma_G = 1.76 \pm 0.09$.

4. Discussion

The results presented in §3 provide clear evidence for transient, spectrally hard HE emission from a point-like γ -ray source that is positionally coincident with the BL Lac object 5C 3.178. The spectral properties and temporal variability of the transient are both consistent with the characteristics of other BL Lac objects that have previously been detected by the *Fermi*-LAT (Ackermann et al. 2011; Şentürk et al. 2013). On the basis of this combined evidence, it seems reasonable to attribute the observed γ -ray emission to a HE flare of the BL Lac object 5C 3.178.

The hard spectral index of the observed HE emission is also consistent with the sub-population of 36 High-Synchrotron-Peaked BL Lac objects (HBLs) that have also been detected at VHE γ -ray energies, all of which have $\Gamma < 2.3$ (Şentürk et al. 2013). Indeed, the moderate redshift of 5C 3.178 suggests that the source may be a viable target for observations by ground-based Cherenkov telescope arrays. Combined HE and VHE γ -ray observations HBLs have been used to probe the properties of the extragalactic background light (e.g. Ackermann et al. 2012; H.E.S.S. Collaboration et al. 2013) and can provide strong constraints on the value of bulk cosmological properties such as the strength of the extragalactic magnetic field (Taylor et al. 2011; Vovk et al. 2012).

Studies of this type invariably benefit from multi-wavelength observations and strictly simultaneous data are

preferred when dealing with variable and unpredictable γ -ray signals. Without an *a-priori* expectation of transient γ -ray emission, achieving this simultaneity requires rapid identification of potential targets in order to coordinate the instruments involved. Atmospheric Cherenkov telescope arrays such as MAGIC II (Aleksić et al. 2012) or VERITAS (Holder et al. 2006) provide good sensitivity above ~ 100 GeV, but are characterised by limited fields-of-view ($\lesssim 5^\circ$) which renders the serendipitous discovery of flaring γ -ray sources using these instruments unlikely. In contrast, continuous survey observation mode of the *Fermi*-LAT effectively guarantees that any transient emission lasting longer than ~ 6 hours will at least be *observed*, although limited sensitivity in the GeV energy range may lead to fainter sources escaping detection.

Systematic blind searches for variable signals within the *Fermi*-LAT all-sky dataset are extremely computationally intensive and can only consider a limited number preselected variability timescales. Currently, automatic monitoring for transient γ -ray signals in the latest *Fermi*-LAT data is provided by the *Fermi* Flare Advocate (FA) service (Ciprini & *Fermi*-LAT Collaboration 2012). This facility performs preliminary analyses that are optimised to search for bright ($F_{E>100 \text{ MeV}} \gtrsim 10^{-6} \text{ phs}^{-1} \text{ cm}^2$) sporadic γ -ray emission within intervals lasting 6 hours, one day, and one week. Restricting transient searches in this manner inevitably sacrifices sensitivity to signals with longer variability timescales. Indeed, if the proposed association with 5C 3.178 is correct the γ -ray signal identified in this work may indicate a population of mildly variable BL Lac objects that are overlooked by the current FA policy. Assum-

ing that this is the case, the temporal characteristics of the observed HE signal appear to motivate all-sky searches for moderately bright γ -ray emission that varies on ~ 100 – 200 day timescales.

5. Summary

Fermi-LAT data have been used to identify a point-like source of transient HE γ -ray emission that is positionally coincident with the BL Lac object 5C 3.178. The probability that 5C 3.178 is the correct association for the transient emission was calculated to be 91%, while a search for alternative counterparts yielded no viable candidates. A temporally resolved analysis yielded a trials-corrected maximum likelihood ratio test statistic of 58.9 (equivalent to $\approx 7.7\sigma$) and localised the observed γ -ray signal to the time interval between MJD 55882 (2011-11-17) and MJD 56102 (2012-06-24). During this interval, the source was characterised by a hard power law energy spectrum ($dN/dE \propto E^{-\Gamma}$) with spectral index $\Gamma = 1.76 \pm 0.09$ and a 0.2–300 GeV flux $F_{0.2-300 \text{ GeV}} = (8.22 \pm 2.04) \times 10^{-9} \text{ ph cm}^{-2} \text{ s}^{-1}$. In combination, these spectral and temporal properties are reminiscent of a limited number of HBLs that have previously been observed by the *Fermi*-LAT, and which are often VHE γ -ray emitters. The detection of 5C 3.178 using ground-based atmospheric Cherenkov telescope arrays would extend the existing catalogue of BL Lacs that have been detected at both GeV and TeV energies, enabling a more secure classification of the source and simultaneously establishing 5C 3.178 ($z \approx 0.25$) as the fourth most distant object in this category⁷. As well as elucidating the intrinsic processes that operate within AGNs, simultaneous HE and VHE observations of distant HBLs can also be used to constrain the properties of extragalactic photon fields or the intergalactic magnetic field.

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⁷ See e.g. <http://tevcat.uchicago.edu>